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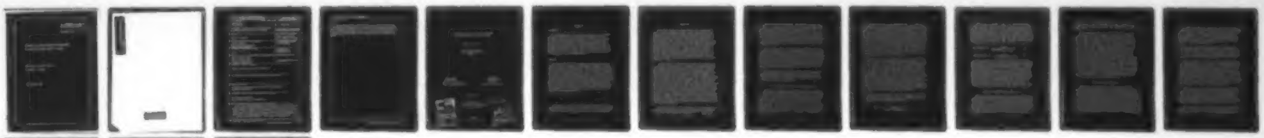

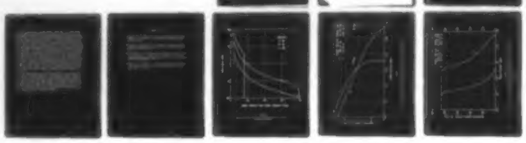

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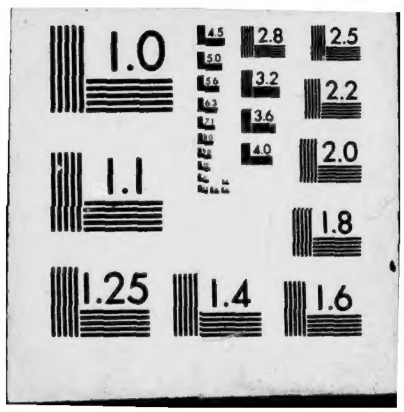
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AD-A034 205

DOSIMETRIC CLASSIFICATION OF MIXED BEAMS OF COSMIC RAY HEAVY NUCLEI IN SPACE

UNIVERSITY OF WEST FLORIDA
PENSACOLA, FLORIDA

15 OCTOBER 1976

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NR 105-860/1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DOSIMETRIC CLASSIFICATION OF MIXED BEAMS OF COSMIC RAY HEAVY NUCLEI IN SPACE		5. TYPE OF REPORT & PERIOD COVERED Interim Report Jan-Sep 1976 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Hermann J. Schaefer		8. CONTRACT OR GRANT NUMBER(s) Office of Naval Research Contract #00014-76-C-0544
9. PERFORMING ORGANIZATION NAME AND ADDRESS Faculty of Physics The University of West Florida Pensacola, Florida 32504		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task #NR105-860
11. CONTROLLING OFFICE NAME AND ADDRESS See #9		12. REPORT DATE 15 October 1976 13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Office of Naval Research Medical & Dental Sciences Arlington, Virginia 22217		15. SECURITY CLASS. (of this report) 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Publication; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Prepared for the Johnson Space Center of the National Aeronautics and Space Administration

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Space Radiation Dosimetry
Heavy Nuclei, Dosimetry of Mixed Beams

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Heavy nuclei of the primary galactic radiation in space can have the same Linear Energy Transfer (LET) yet greatly different energy distribution patterns in the microstructure of tissue. Therefore, the LET distribution as it is commonly used for dosimetric classification of mixed beams of conventional nuclear radiations is inadequate for heavy particles. The study proposes to replace, for heavy particles, the LET distribution by the energy density (ED) distribution. The formalism for establishing the ED

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distribution is derived and the distributions by volume and energy are presented for two complementary mixed beams of Z = 26 particles with energy spectra from zero to 70 and from 70 to 760 Mev/nucleon. It is shown that both types discriminate well the two different energy spectra. Which type would reflect more accurately the differences in biological effectiveness can only be decided by comparative experiments.

DOSIMETRIC CLASSIFICATION OF MIXED BEAMS OF COSMIC RAY HEAVY NUCLEI IN SPACE

Hermann J. Schaefer

Office of Naval Research
Contract N00014-76-C-0544
Report 1

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SUMMARY

THE PROBLEM

The radiation hazard to astronauts in space from cosmic ray heavy primaries (so-called HZE particles) is at present incompletely understood. Interest of radiobiological research centers on local effects (so-called micro-lesions) which the columns of extremely dense energy dissipation of single traversals of HZE particles produce in cellular tissue. The radial energy density profile is the customary way of describing these columns in quantitative terms. As long as the investigation remains limited to the local effect, the radial profile furnishes complete dosimetric information. However, it does not lend itself easily to a concise dosimetric quantification of total-body exposure to a mixed beam of HZE particles as it affects the crew on a manned space mission.

FINDINGS

The report proposes the use of the compound energy density distribution by volume or by energy for the dosimetric representation of mixed beams. Complete distributions of the two types are derived for complementary segments of a particle track of Z=26 and 24 cm total length in tissue. It is shown that the different energy spectra which the track segments represent are reflected in conspicuous differences of their respective compound distributions by volume as well as by energy. Which of the two types of distributions would distinguish more accurately the differences in the biological effectiveness of mixed beams of different composition can only be decided by actual biological experimentation testing total-body effects from exposures to such beams. Yet even before such data become available, compound energy density distributions should prove useful for concise dosimetric classification and distinction of different HZE particle exposures as they occur on manned missions with different orbital parameters as well as for biological experimentation with heavy ions from accelerators in ground-based laboratories.

The basic content of this report has been presented by the author on 5 April 1976 at Ames Research Center before a select panel of the American Institute of Biological Sciences under the chairmanship of Dr. G. W. Casarett in a conference sponsored by the Office of Life Sciences of the National Aeronautics and Space Administration.

INTRODUCTION

Heavy nuclei of high energy, dubbed HZE particles by radiobiologists, represent a component of galactic radiation in space whose mode of action on living matter is as yet incompletely understood. Expressed in terms of the conventional dosimetric unit rad (roentgen absorbed dose) the energy dissipated by heavy particles constitutes only a very small fraction of an astronaut's total radiation exposure in space. However, the extremely high energy concentration in the microstructure of tissue renders even the single traversal of a heavy particle a potentially harmful event for the individual cell. Obviously, a dosage unit denoting the mean absorbed energy in a larger tissue volume is meaningless if applied to heavy particle exposure. A complete departure from conventional concepts is needed in developing a dosimetric system for HZE particles. As a first step, the basic physical parameters of a heavy particle exposure have to be analyzed. Accordingly, theoretical and experimental efforts of a number of investigators have been directed toward the study of the structure of heavy particle tracks in various media.

An earlier report (1), hereafter referred to as Report 1214, presents a brief review of the theory of track structure. It demonstrates the basic features of the energy dissipation of HZE particles in the microstructure of tissue with graphs and tables of radial energy density (ED) profiles for tracks produced by particles of various Z numbers and energies. By its very nature, the radial ED profile can only describe track structure for the individual event of passage of one particle with exactly defined Atomic Number Z and energy E. As long as radiobiological research centers on the problem of the so-called micro-lesion, i.e., the local tissue damage from one traversal of a heavy particle, the radial ED profile provides complete dosimetric information on the physical parameters. While such scientific inquires into the local effect are quite essential for a better understanding of the mode of action of HZE particles on living matter (2), one should not lose sight of the fact that under operational conditions in space crew members are subjected to total body irradiation with an extremely heterogeneous mixture of HZE particles of different Z numbers and energies. A better understanding of the significance of such exposures from the standpoint of radiological health calls for experiments studying total body effects of mixed beams of HZE particles on test animals. For the dosimetry of such total body irradiation ways and means have to be found for a concise representation of the variety of different individual ED profiles superimposed on each other at any point of observation in the exposed specimen.

The problem is similar to the one concerning the continuum of different Linear Energy Transfer (LET) values of a mixed beam of conventional nuclear radiations, such as protons or alpha particles with different energies. In the latter case, it is common practice (3) to establish the LET distribution, i.e., a graph or table which

breaks down the total absorbed energy into fractions contributed by small incremental LET intervals and to compute the mean Quality Factor (QF) by appropriately weighing the fractions. To mixed beams of HZE particles the just explained enviably simple method is not applicable because LET does not differentiate track structure. Two different HZE particles, one of high and the other of low Z and E, can have the same LET yet greatly different radial ED profiles. Although little is known about the nature of local damage from tracks with the same LET yet different radial structures of their ion columns, it seems a foregone conclusion that the damage should be different. It is seen then, that for mixed beams of HZE particles a dosimetric representation is needed which describes the exposure concisely yet preserves and reflects its particular microdosimetric make-up.

The idea is near at hand to use, for the indicated dosimetric identification of a mixed beam, the ED distribution. Examining the concept in more detail, one realizes that there are two possible representations, the ED distribution by volume and the ED distribution by energy. Although either form appears to differentiate well heterogeneous beams which produce identical absorbed doses yet possess different Z and E spectra, the one which reflects best the biological effectiveness obviously should be given preference. At the present state of the art with hardly any data on total body exposures to mixed beams of HZE particles available, no criteria for deciding the indicated alternative exist. The answer can come only from radiobiological experimentation comparing mixed beams with different Z and E spectra.

The following theoretical study presents the mathematical formalism for establishing the ED distributions by volume and energy and examines how well they distinguish spectral differences of mixed beams with special emphasis on the region of very high ED values which presumably act on living matter in a way basically different from conventional nuclear radiations.

THE ED DISTRIBUTION AND THE RADIAL ED PROFILE

The ED distribution directly derives from the radial ED profile by simple coordinate transformation. Compared to the radial profile, it has the distinct advantage that it can be established not only for the individual event but also for a mixed beam containing any number of different profiles under full preservation of the contiuum of ED values represented in the beam. The theoretical background and mathematical formulae for establishing the radial ED profile for a particle of given Z and E is reviewed in Report 1214. In order to connect with the earlier presentation, we present in Figure I three selected radial profiles for a particle of Z = 26 with energies of 760 and 70 and 20 Mev/nucleon corresponding to beta values of 0.83 and 0.37 and 0.20. We point out again that local energy density is expressed in rad units interpreting the definition of the rad differentially as the energy dissipated in a vanishingly small tissue volume divided by that volume. It is seen that the three radial profiles show

greatly different radial extensions as well as absolute values. If we visualize in a conceptual experiment two tissue samples irradiated with different mixed beams one of them containing all energies between 20 and 70 and the other between 70 and 760 Mev/nucleon, it is quite obvious that the respective mean profiles would not furnish meaningful microdosimetric representations of the two different exposures. Clearly, the mean between two greatly different ED values completely obliterates the radiobiologically most important magnitude. However, a more adequate microdosimetric description can be obtained by abandoning the geometrical concept and plotting, over an abscissa scale showing ED, the combined fractional volumes within which the same ED prevails. Going one step further and multiplying the fractional volumes by their respective ED values, we obtain the fractions of the total energy dissipation which we plot over the same abscissa. The first operation furnishes the ED distribution by volume and the second the ED distribution by energy. Although we lose in the process the direct geometrical representation of individual events, we preserve the complete spectrum of ED values as it actually prevails in an irradiated tissue volume and gain at the same time a unified representation of it.

In examining more closely the changes that occur in the radial ED profile as the particle energy decreases, for instance, from 70 to 20 Mev/nucleon, i.e., from Curve B to A in Figure 1, we see a substantial decrease of the penumbra radius accompanied by a substantial increase of local ED values in the remaining penumbra of smaller size. Since interest centers on high and very high ED's, we will have to direct our attention in the assembly of the compound distribution especially to the region of small and very small radii at and well below the left end points of the truncated profiles shown in Figure 1. In fact, local ED's well in excess of 100 rad selected in Figure 1 as an arbitrary limit occur even in tracks of conventional nuclear radiations such as protons or alpha particles (4). The real test for the practical usefulness of a new dosimetric system, then, is the examination of that part of a compound distribution that reflects the region of the penumbra near the center of the track. Accordingly, we have limited the analysis of the two complementary segments of the Z=26 track to the region above 10^3 rad. Detailed inspection of individual profiles at such high values calls for an abscissa scale of much higher resolution that the one shown in Figure 1. The reader will find such plots in Report 1214.

The compound ED distribution of a mixed beam is obtained by summation of all individual ED distribution represented in the beam. Mathematically, the step from the radial ED profile to its counterpart individual ED distribution is simple. The basic equation for the radial profile (Report 1214) reads:

$$D = \frac{L_\infty}{4\pi r^2 \ln(\sqrt{e}\, r_p / r_c)} \qquad (1)$$

where D stands for the ED, L_∞ for the LET_∞, r for the radial distance from the track center, ln for the natural log, e its basis, and r_p and r_c for the penumbra and core radius respectively. Since D varies over a range of several powers of 10, it is advisable to establish ED distributions over a log rather than a linear scale of D. This method is also preferable because LET distributions for conventional radiations are usually presented on a log LET scale. Analytically, this proposition means that we have to determine dV/d(log D) and dE/d(log D) rather than dV/dD and dE/dD. The differential volume dV for a cylindrical track of unit length is defined by the equation $dV=2\pi r\,dr$. Using the relationship $\frac{dV}{dD} = \frac{dV}{dr} \cdot \frac{dr}{dD}$ and remembering that d(log D)/dD=1/D log e, we obtain:

$$dV/d(\log D) = \frac{L_\infty}{4D\ln(\sqrt{e}\, r_p/r_c)\log e} \qquad (2)$$

$$dE/d(\log D) = \frac{L_\infty}{4\ln(\sqrt{e}\, r_p/r_c)\log e} \qquad (3)$$

It is seen that the distribution by volume shows a simple reciprocal dependence of the differential volume on ED whereas the distribution by energy shows the differential energy dissipation as constant throughout the entire log ED scale. To be sure, the foregoing two statements hold only for the distribution representing an individual event with constant values of L_∞, r_p, and r_c. As soon as we proceed to the analysis of the compound distribution of a mixed beam, a continuum of individual distributions differing in their respective extensions on the log D scale has to be integrated. This operation leads to a more complex configuration of the resulting compound distribution. As indicated repeatedly, interest in the present context centers on the upper end of the compound ED distribution which reflects the highest D values prevailing in a specimen irradiated by the mixed beam. To examine how sensitively this particular section of the distribution reacts to changes in the Z and/or E composition of the beam is the basic issue of this entire study.

DETAILS OF COMPUTATIONAL ANALYSIS

Rather than immediately engaging in the extensive analysis of a complex Z and E spectrum of HZE particles as it would actually be encountered in space, we have limited ourselves in this pilot study to the evaluation of two complementary sections of a single track os Z = 26. Visualizing the particle entering a tissue layer at an energy of 760 Mev/nucleon, we divide its total path in tissue of 24 cm length into a high-energy section covering the energy interval from 760 to 70 Mev/nucleon and a terminating low-energy section from 70 to zero Mev/nucleon. The two sections correspond to track segments from 24 to 0.36 to zero cm tissue respectively. A comparison of the distributions for the two complementary sections should test the

response to changes in the E spectrum, especially in the low-E region. This region is of particular interest from an operational viewpoint because galactic radiation in space varies, on different types of missions, with regard to the low-energy cutoff of the spectrum.

The distribution by volume or energy for local passage of a single particle, i.e., for a specific triplet of values LET_∞, r_p, and r_c, can be established analytically from Equ. (2) and (3). However, for assembling the compound distribution of a longer track segment with the three coefficients varying continuously, numerical integration is the appropriate method. We have conducted the analysis as follows. The total track length of R = 24 cm was subdivided into 27 sections with R increments per section progressively larger beginning from R = O cm in such a way that the percentage LET variation remained approximately constant in all R sections. LET_{mean} and its corresponding r_p and r_c values were considered as constant within each R section and used as representative coefficients. In a similar fashion, the D scale was subdivided into intervals of equal log width Δ (log D) = 0.2 and log D_{mean} was used as constant representative value for each interval. The differential volumes and energies for the indicated constant interval width were then computed for all D intervals and R sections using Equ. (2) and (3). All Δ V and Δ E contributions for the same log D_{mean} then were added separately for the high-E and low-E segment of the track. Each sum represented one ordinate value of the respective distribution for the abscissa value log D_{mean}. The uniform subdivision of the log D scale creates repetitive number sequences for the resulting Δ V and Δ E values with only the decimal place shifting from one log decade to the next. This greatly simplifies the computational process and should keep the work load within manageable limits even for mixed radiation fields substantially more complex than the system analyzed in this preliminary study.

RESULTS AND CONCLUSIONS

Figure 2 presents the compound ED distributions by volume for the two complementary track segments defined above. The ordinate shows, on a log scale, the differential volume in relative units for the constant abscissa interval Δ (log D) = 0.2. The abscissa itself shows ED in rad units on a log scale with ED values below 10^3 rad omitted for reasons explained before. It is seen from Figure 2 that for both the low-E (Curve B) and the high-E (Curve A) segment of the track the values of the differential volume extend over an extremely wide range varying by a factor of more than 10^8. In the region of low and medium ED's, the differential volume changes inversely with ED in a linear relationship dropping by a factor of 10 as ED increases by the same factor. However, as ED approaches its maximum at the right end of the distribution, the volume drops more rapidly and, in its final approach to the terminal point, precipitously. The distributions for both track segments show basically the same configuration yet terminate at maximum ED values differing by a factor of about 100 with the larger value belonging

to the low-E segment.

The strong inverse dependence of the differential volume on ED illustrates well the basic characteristic of any HZE particle exposure that the tissue volumes containing very high ED values at the upper end of the distribution are extremely small both in relative and absolute terms. This fundamental proposition finds its accurate quantitative expression in the ED distribution by volume quite differently from the radial ED profile which can furnish only a topological description of the energy distribution for individual events yet does not lend itself directly to a dosimetric interpretation of exposures to a complex beam.

Progressing from the foregoing general appraisal of the ED distribution by volume to the specific objective of our analysis, we turn to the question of how well the two distributions distinguish the two different track segments. At medium and low ED's, the two distributions differ little following straight lines parallel to each other. However, in the region of high ED's they exhibit distinctly different patterns intersecting each other and terminating at greatly different maximum ED values.

It appears paradoxical at first sight that in the parallel region the distribution for the high-E track segment (Curve A in Figure 2) shows larger differential volumes than the low-E segment (Curve B). The explanation is to be found in the fact that at high energies the three parameters LET_{∞}, r_p, and r_c vary much more slowly per unit length of path than at low energies. A given ED, therefore, prevails in a cylindrical surface of greater length although of smaller radius and the former overcompensates the latter making the resulting total volume larger. Since, at the same time, particle energy and maximum ED are inversely related, the distribution of the high-E track segment terminates at a lower maximum ED than the one of the low-E segment. Therefore, the two distributions must intersect. They resemble in this respect the radial profiles of individual events for particles of different energies as can be seen from Figure 1. However, the underlying mechanisms are quite different.

We have seen that the greatly different extensions on the ED scale and the point of intersection make the two distributions conspicuously different. The ED distribution by volume thus appears to qualify as a dosimetric representation that will distinguish well different mixed beams or radiation fields of HZE particles. To what extent the ED distribution by volume would also be representative of the respective tissue damage from HZE particle beams of different composition can only be decided by radiobiological experimentation comparing the effects of such beams. A speculative discussion of these aspects is beyond the scope of this treatise.

Turning to the second kind of distribution, we examine in Figure 3 the ED distributions by energy for the same two track segments analyzed in Figure 2. The curves in Figure 3 show fractions of the total energy dissipation for the same constant abscissa interval $\Delta(\log D) = 0.2$ used before. Although derived faster and more ele-

gantly from the equation for the radial profile as shown above, the curves in Figure 3 could be obtained directly from those of the distributions by volume in Figure 2 by multiplying each ordinate value by its corresponding abscissa value since the product of a fractional volume and the ED prevailing in it represents the fraction of the total energy dissipation contributed by the volume. It is seen by inspection that for the region where the differential volume is inversely proportional to ED the product must remain constant for all ED's. Accordingly, we see in Figure 3 the regions in question represented by horizontal plateaus in both distributions. However, this does not mean that the compound ED distribution by energy is insensitive to changes in the composition of a mixed beam. In a similar way as the distributions by volume in Figure 2 reflect such changes in their upper sections turning from a rectilinear to a curvilinear course, the distributions by energy in Figure 3 do so in the same sections changing from a horizontal straight line to a steeply declining curve. It is seen, then, that the ED distribution by energy is a stomg competitor to the one by volume. This is all the more so because in the dosimetry of conventional nuclear radiations the LET distribution by energy also is the preferred method for comparing mixed radiation fields of different composition. Again, however, the final word in deciding the alternative has to be spoken by the radiobiologist on the basis of experimental data comparing the effects of mixed HZE particle beams of different composition on biological specimens.

At the present state of the art, experimental data of the just indicated kind are not likely to become available soon. In the meantime, however, the proposed new dosimetric system opens the way to compare different HZE particle spectra as they are encountered on manned space missions with different orbital parameters and to do so more concisely and in radiobiologically more meaningful terms than this is accomplished with the complex Z and E spectra of the physicist. Similarly, the ED distribution should be a useful concept in evaluating biological experiments with heavy ions from accelerators in ground-based laboratories where particle beams over a wide range of Z and E values are now available.

REFERENCES

1. Schaefer, H. J., Microdosimetric Structure of HZE Particle Tracks In Tissue. NAMRL-1214. Pensacola, Fla.: Naval Aerospace Medical Research Laboratory, 1975.

2. Chatterjee, A., Maccabee, H. D., and Tobias, C. A., Radial Cutoff LET and Radial Cutoff Dose Calculations for Heavy Charged Particles in Water. Rad. Res. 54, 479-494, 1973.

3. Howard-Flanders, P., Physical and chemical mechanisms in the injury of cells by ionizing radiation. In Tobias, C. A., and Lawrence, J. H. (Eds.), Advances in Biological and Medical Physics. Vol. VI. New York: Academic Press, 1958, pp. 553-603.

4. Wingate, C. L., and Baum, J. W., Measured Radial Distributions of Dose and LET for Alpha and Proton Beams in Hydrogen and Tissue-Equivalent Gas. Rad. Res. 65, 1-19, 1076.

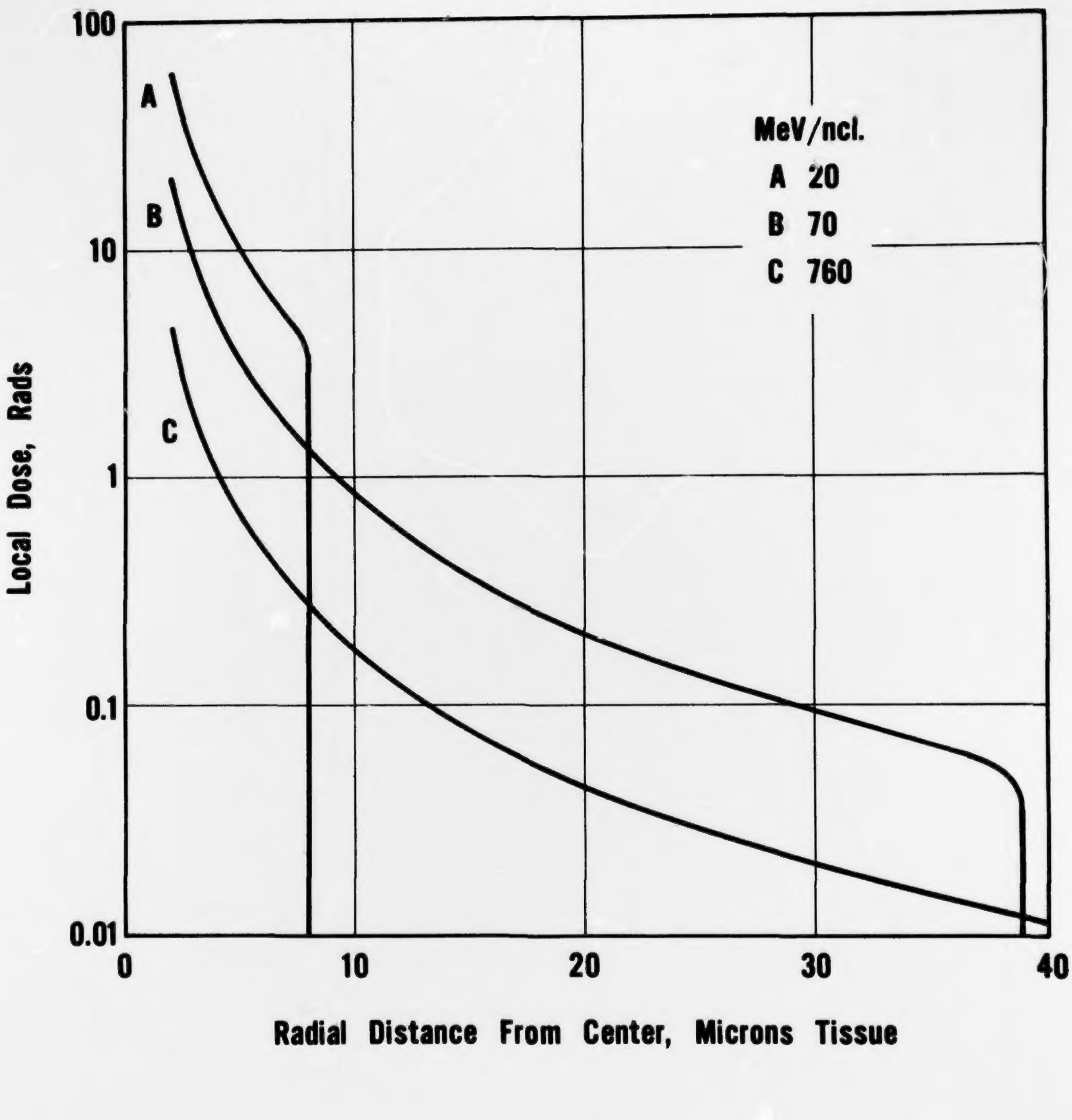

FIGURE 1

Radial Energy Density Profile for HZE Particle Track of Z = 26 and Three Different Energies

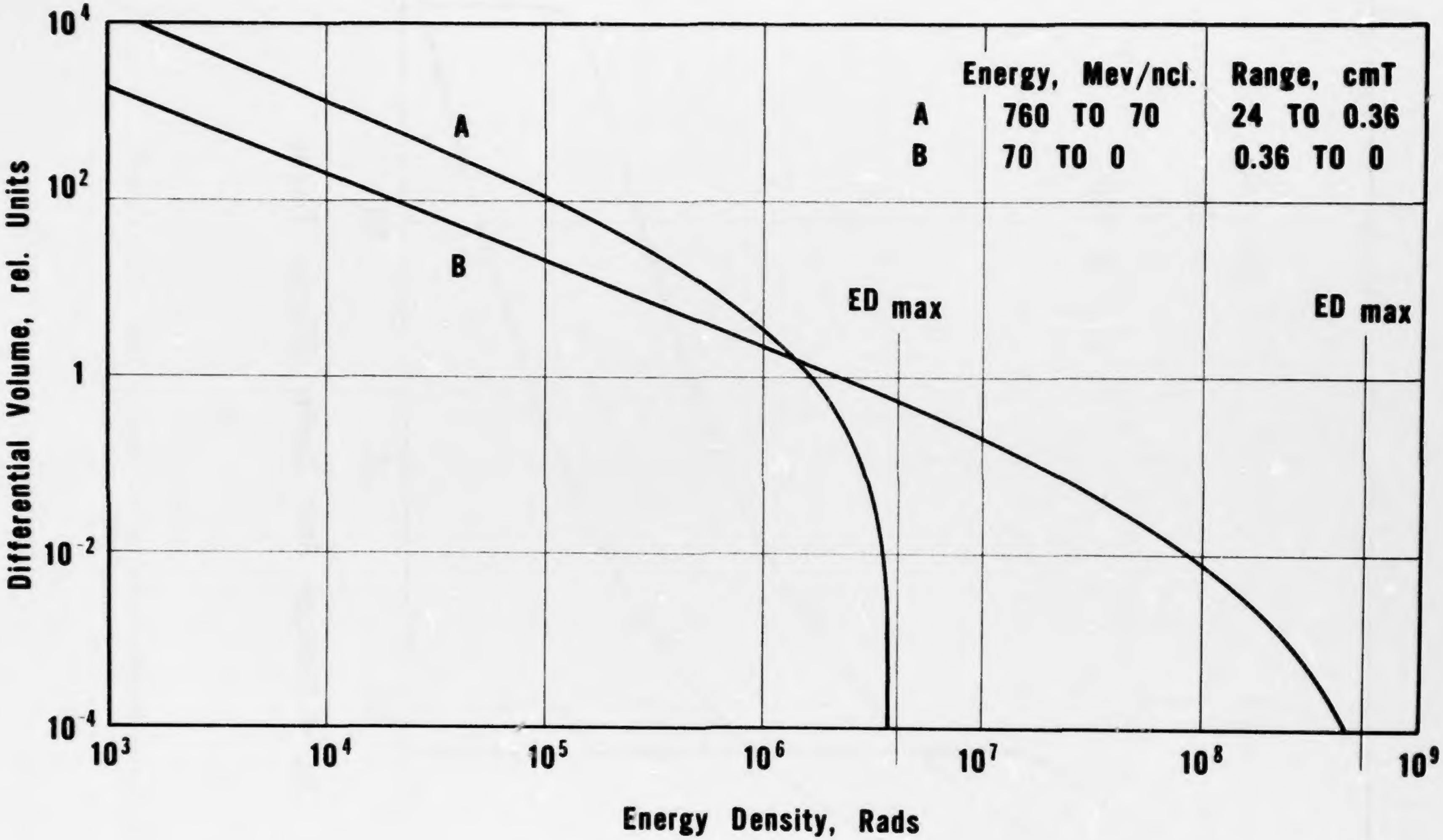

FIGURE 2

Energy Density Distributions by Volume for Two Complementary Sections of HZE Particle Track of Z = 26

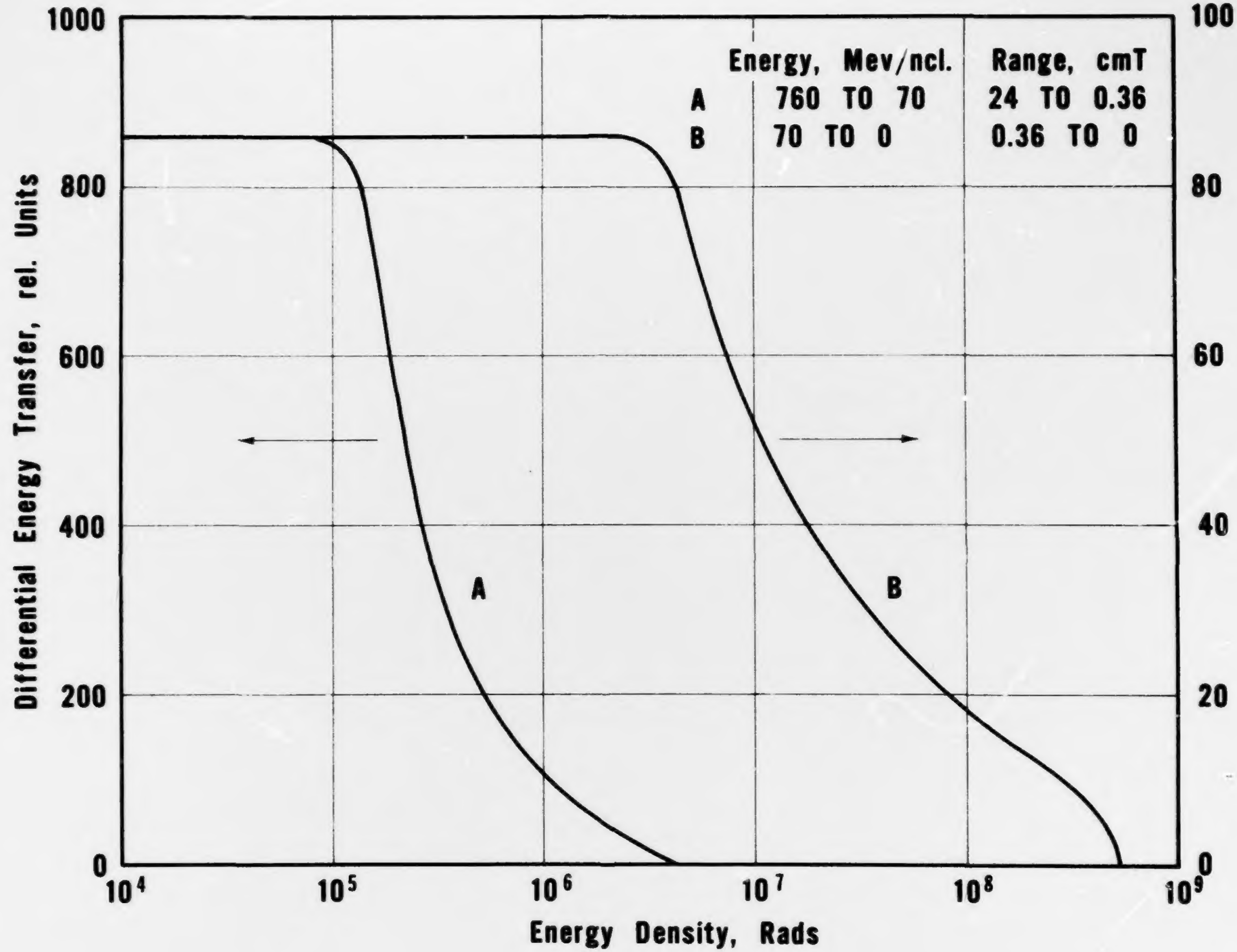

FIGURE 3

Energy Density Distributions by Energy for Two Complementary Sections of HZE Particle Track of Z = 26